INFRASOUND IN THE "ZONE OF SILENCE"

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ABSTRACT

Two controlled source experiments were conducted in Nevada in 2006 and 2007 to study infrasound signal propagation at distances less than 300 km from the source. This area around a source is sometimes referred to as the "zone of silence" because, based on ray theory, no infrasound energy is expected to return to the ground. However, many observations of returned infrasound energy have been made at these distances.

In 2006, three temporary infrasound arrays were deployed at distances of 76, 108 and 157 from the source. In 2007, the site at 157 km was reoccupied, and data were also recorded at 288 km from the source. These arrays were supplemented with data from the permanent Nevada Infrasound Array (NVIAR), located 37 km from the source. In addition, meteorological data from balloon launched rawinsondes were collected in the path of the propagation.

Interesting results were derived from the travel time analysis. In 2006, the site at 76 km recorded both tropospheric and stratospheric arrivals, while at 108 and 157 km only stratospheric arrivals were recorded. In 2007, the site at 157 km recorded both tropospheric and stratospheric arrivals, while at 288 km both stratospheric and thermospheric arrivals were recorded. While stratospheric arrivals appear most frequently, atmospheric modeling with the InfraMAP software, did not predict these arrivals. Current modeling efforts focus on the tropospheric arrivals.

Amplitude variations at NVIAR for sources with the same yield varied more than an order of magnitude on two consecutive days. The site located 157 km from the source observed variations by a factor close to five. We therefore attempt to estimate the yields of the explosions using the predominant frequency content of the signals. The physical basis for such a method is found in an increased acoustic transit time of the explosion blast radius with increased yield. Past formulas were developed for old nuclear atmospheric explosions, but no extrapolation to the lower yields was ever performed. In the current work we use controlled sources with explosive yields of 2000–4,000 lbs. in order to verify the applicability of such a scale to lower yields. Preliminary results show that this is possible.

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OBJECTIVES

The primary objective of this research study is the propagation of infrasonic waves at distances up to 300 km from the source. This area, extending up to 300 km from the source has been called the "Zone of Silence" because classical ray theory does not predict any infrasound arrivals. However, under appropriate wind and temperature conditions, infrasound recordings in the "Zone of Silence" were reported several times (McKenna, 2005; Golden et. al. 2007).

RESEARCH ACCOMPLISHED

Two controlled source experiments were carried out in 2006 and 2007 near Hawthorne, NV, where ammunition disposal operations take place on a regular basis. Shown in figure 1 is the location of the Nevada Seismic Array (NVAR) and the configuration of infrasound array. Also shown is the location of the disposal pits (dubbed New Bomb) and NVAR recordings of a typical disposal operation. In a typical operation day a suite of five explosions is recorded at NVAR, but the number of explosions in a day could vary from 3 to 10, depending on the nature of operation.

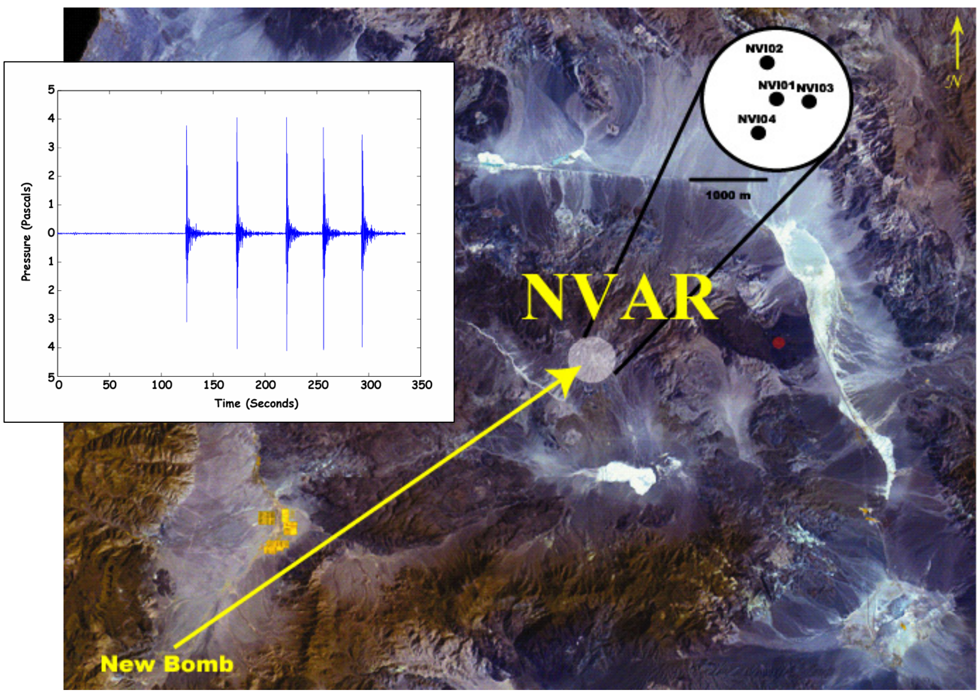

Figure 1. Location of NVAR and the ammunition disposal site (New Bomb). Also shown are the NVIAR configuration and a typical NVIAR recording of the detonations.

During the 2006 experiment, three 4-element temporary arrays were installed north of New Bomb, at distances of 76, 108 and 157 km. The array at 76 km was located within the village of Shurz NV (SHURZ), while the other 2 arrays were north and south of the city of Fallon, NV, designated Fallon north (FALN) and Fallon south (FALS), along State Highway 95. In the 2007 experiment, the site at FALN (157 km) was reoccupied, and a new temporary array was installed at 288 km from the source, north of Gerlach, NV (GERL). The locations of the temporary arrays and the individual layouts are shown in Figure 2. Each of the portable arrays consisted of 4 IML infrasound sensors located in line with the direction of propagation of the signals at separation distances of 50, 100, and 150 meters. The linear configuration was chosen to maximize the time delays across the array. In the 2006 experiment, data were collected for three days, while in the 2007 experiment, data was collected for four days.

In addition to the infrasound array data we collected meteorological data at the Hawthorne NV airport. We employed the National Severe Storms Laboratory (NSSL) to collect balloon launched rawinsonde meteorological data during our three experiment days. The rawinsondes were used to collect temperature, dewpoint, barometric pressure, GPS latitude, longitude, altitude, and wind speed and direction data.

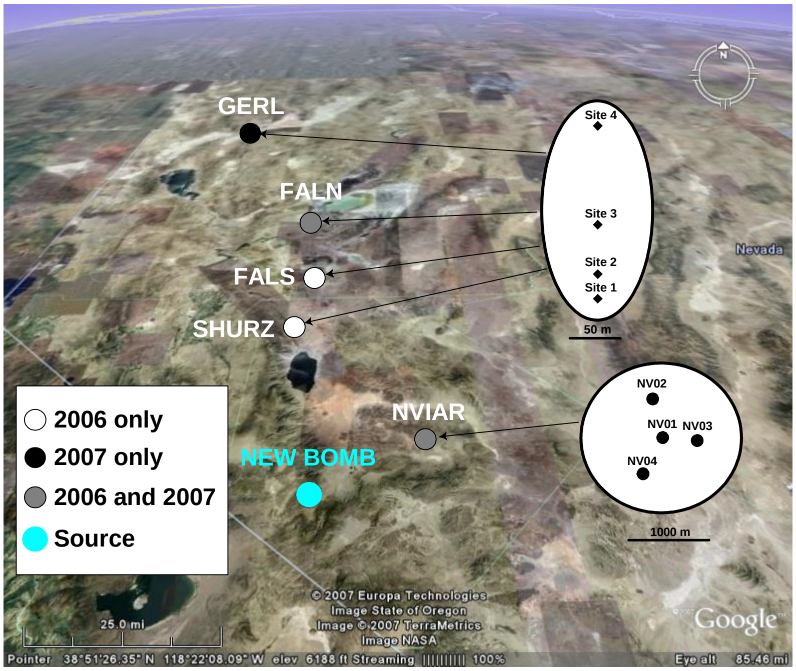

Figure 2. Satellite image of the area of temporary infrasound arrays deployed for the experiments with plan layouts of each array.

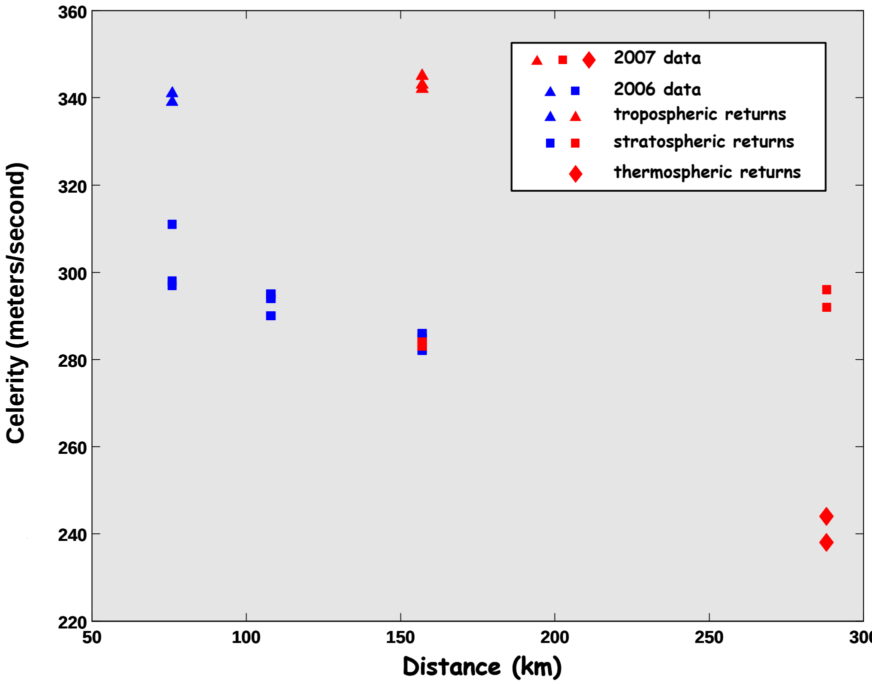

Figure 3. Infrasound mean travel velocity (celerity) at each array for all observed arrivals.

Interesting results were derived from the analysis of the travel time. Celerity (distance divided by the total travel time) was used as an indicator for the nature of recorded signals (Muntschlecner and Whiteker, 1999; Kulichkov et al., 2000). The celerity values are shown in Figure 3. In 2006, most of the recorded signals were stratospheric (celerities of 310–284 meters/second). Only SHURZ (76 km form the source) recorded a low tropospheric arrival (Figure 4) for the first two days of the 2006 experiment (celerities around 340 meters/second). In the 2007 tropospheric, arrivals were recorded at FALN during all days of the

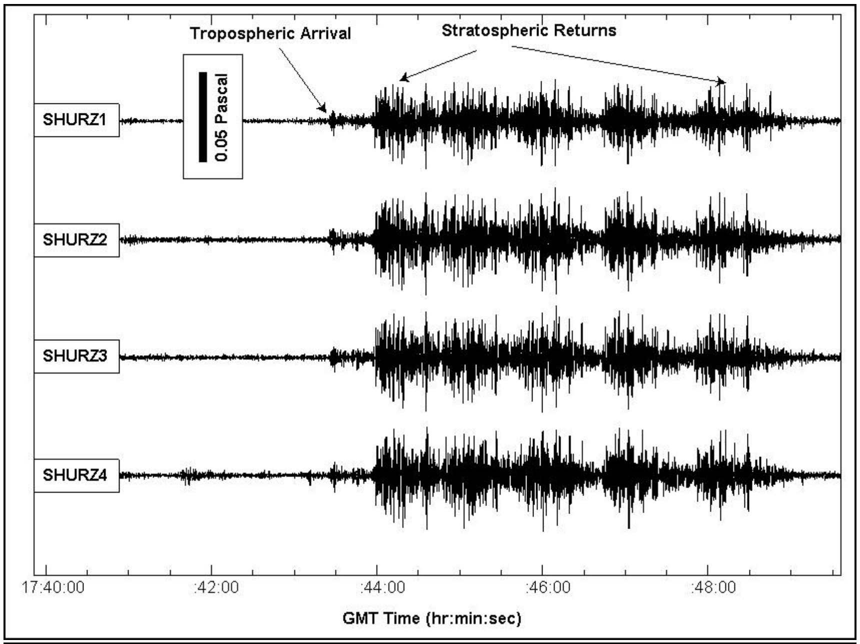

Figure 4. Data recorded at SHURZ (76 km) during the 2006 experiment. Approximately 30 seconds before the arrival of the main wavetrain a low tropospheric arrival was recorded. Any other subsequent tropospheric arrivals would be masked by the much higher amplitude stratospheric signals.

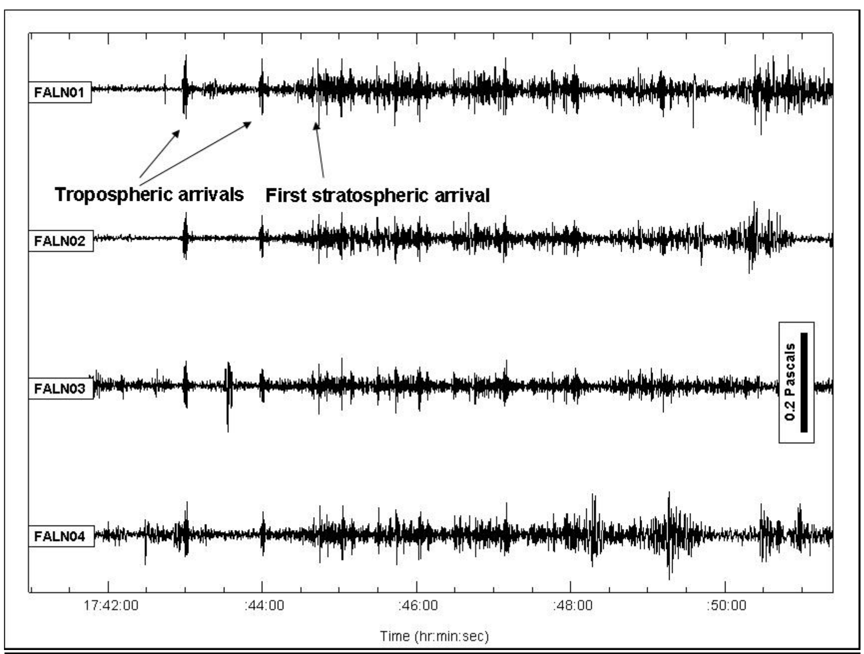

Figure 5. Tropospheric and stratospheric signals recorded at FALN (157 km) during the 2007 experiment. After the tropospheric signals from the first two explosions, there is mixture of stratospheric and tropospheric signals.

experiment. Figure 5 shows the FALN recording for Julian day 255. After the first two tropospheric signals, there is a wavetrain that is interpreted as a mixture of stratospheric and tropospheric signals. This combination of tropospheric and stratospheric signals was observed for the first three days of the 2007 experiment, while in the fourth day only tropospheric signals were observed. For the array at Gerlach (288 km), signals were observed for only two days of the experiment, while during the other two days of the experiment, the local noise conditions were significantly higher. GERL recorded a combination of stratospheric and thermospheric arrivals (celerities of 296 for stratospheric and 240 for thermospheric arrivals). The first thermospheric signal is recorded before the arrival of the last stratospheric signals (Figure 6). No tropospheric arrivals were observed at GERL.

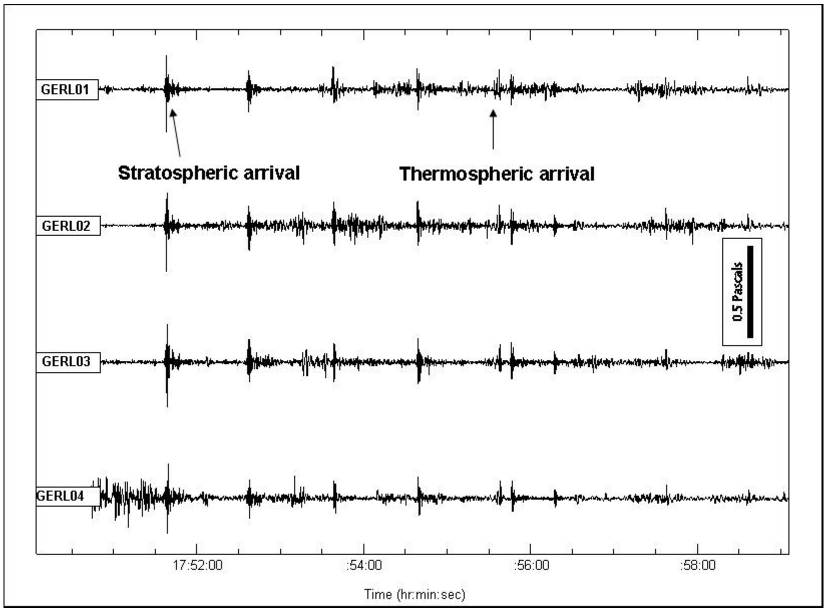

Figure 6. Thermospheric and stratospheric arrivals recorded at GERL (288 km from the source). The first thermospheric arrival is observed after four stratospheric arrivals, before the last stratospheric signal.

In addition, the carefully controlled explosive yields enable us to investigate various scaling relationships for yield. As we have observed in the past, amplitude variations more than one order of magnitude for infrasound signals recorded in similar conditions, we decided to use a relationship between the yield and dominant period of the signal. Such a relationship was developed from a suite of atmospheric nuclear explosions:

$$Y = 2.38 \cdot T^{3.34} \qquad (1)$$

Spectral estimates are typically obtained using Fourier-based methods which provide a relative measure of the energy at each frequency. For simple periodic signals the estimates might be accurate, but for real data with noise the Fourier methods provide a very poor estimate of the spectrum. Various windowing techniques were developed to reduce the variance of the spectral estimates (Blackman and Tuckey, 1959; Welch, 1967), but they tend to spread the energy over adjacent frequencies. An alternative way to obtain spectral estimates is the AR method (Priestly, 1981). The AR method is a parametric method, widely used in statistics and has direct applications in many areas of interest. The method provides an estimate of the spectrum and the fundamental (or system) frequencies of the time series. For a quick comparison of the methods Figure 13 shows the power spectrum estimate of a time series obtained with a simple periodogram, a windowing technique (Welch, 1967), and an AR method. By far the best estimator is the AR method.

An important problem in using AR methods is the order selection. The higher the order, the better the spectrum estimates will be, but the more difficult it is to interpret. In our case, the order selection was

performed empirically so that the potential noise bias on the frequency estimate is reduced. By adding noise before the arrival of the infrasound signal, and estimating the spectrum of signal and noise repeatedly, we found out that for orders higher than 16 the noise bias is significantly removed, even in the case of a signal with a low signal to noise ratio. The accuracy of the frequency estimates with an AR(16), for which the coefficients were determined with Burg's maximum entropy method (Burg, 1972), was tested with a bootstrap algorithm and it was found to be extremely reliable. The standard deviation of 5,000 realizations was determined to be below 0.15 Hz (Figure 7).

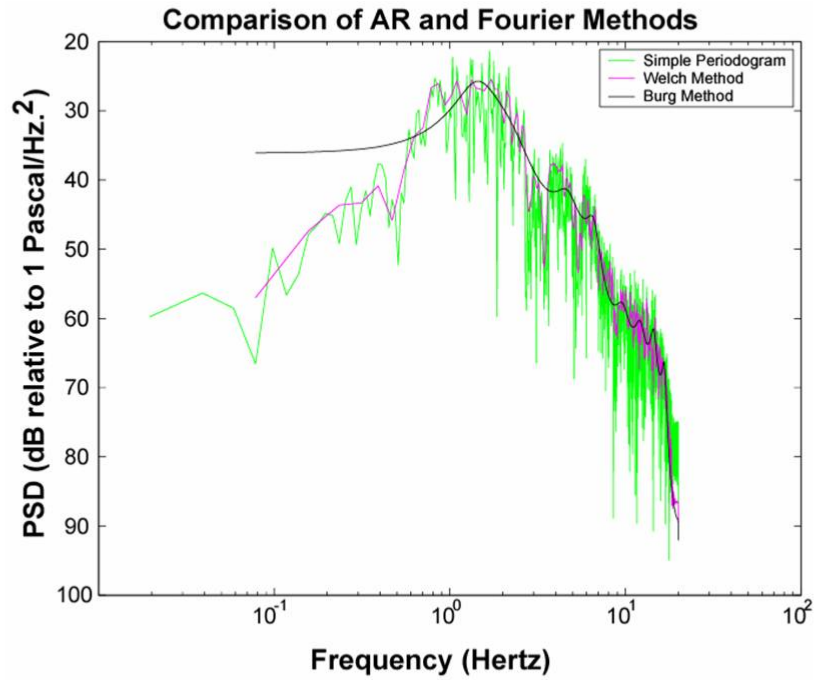

Figure 7. Comparison of AR and Fourier methods.

CONCLUSIONS AND RECOMMENDATIONS

Infrasound modeling was performed with the InfraMAP software developed by BBN Technologies. Shown in figure 8 are the results of the modeling using the Naval Research Lab Ground-to-Space (NRL G2S) model for the 2007 data. The G2S model is supposed to include the local meteorological variations. The left plot shows the ray-tracing results, and the right shows the pressure amplitude field (in dB) obtained with the parabolic equation (PE) code. The locations of our arrays are shown on the left plot. On that particular day FALN recorded tropospheric and stratospheric signals, while at GERL we observed stratospheric and thermospheric signals. None of the actual arrivals are predicted with either of the method. Thermospheric rays are predicted to bounce at more than 350 km away from the source, while raytracing shows no stratospheric or tropospheric rays. These results are similar to the PE code.

Current modeling efforts focus on using the actual meteorological data acquired in the paths of the propagating signals to determine the presence of any potential duct in the troposphere that could have allowed the transmission of energy to greater distances. In addition, this controlled dataset will allow us to investigate the relationship between the celerity and the phase velocity (which in ray theory is supposed to be equal to the effective sound speed velocity in the place where that particular ray is turning).

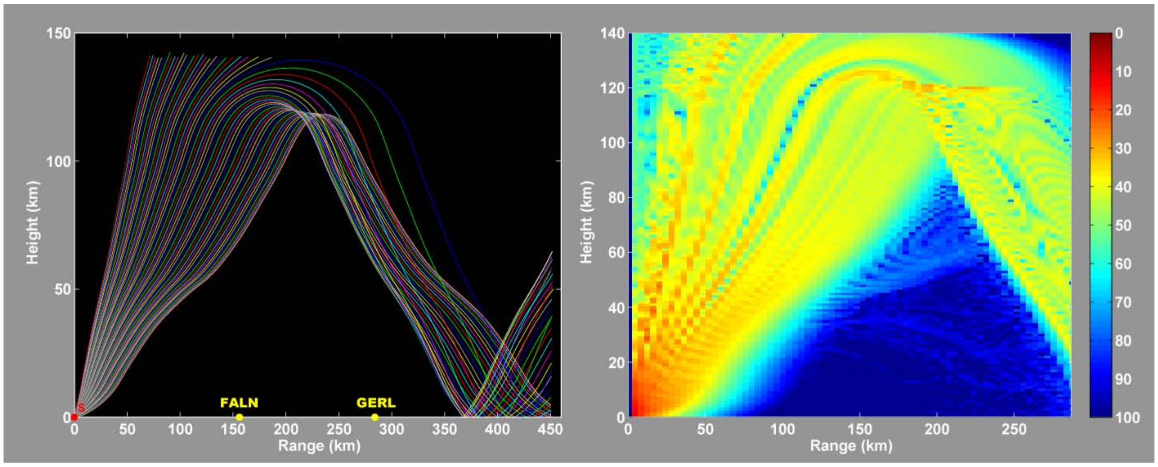

Figure 8. Ray tracing (left) and PE calculations through the NRL G2S model for the 2007 data. The model is supposed to include the meteorological effects below 20 km.

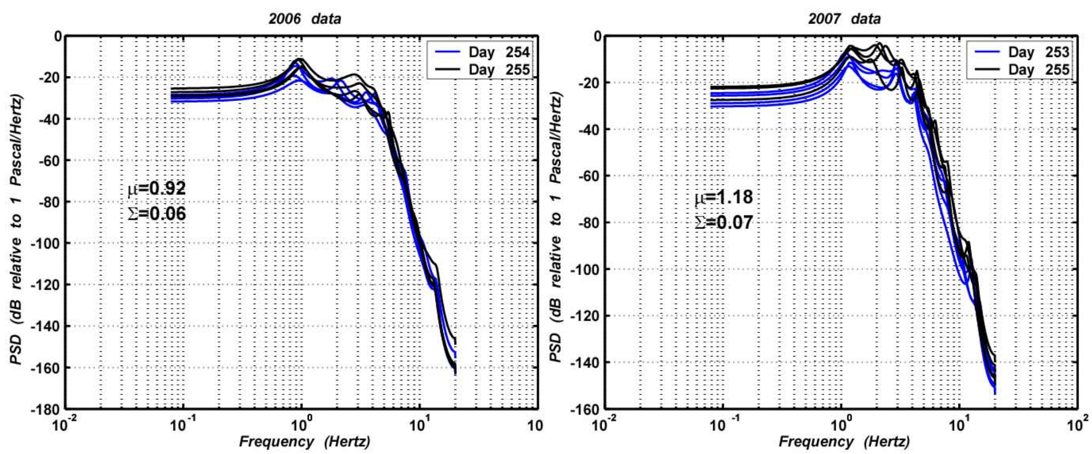

Figure 9. AR estimates for different days for 2006 and 2007 data at NVAR.

Frequency estimates for 2006 and 2007 datasets were obtained with an AR(16) method. Figure 9 shows the Power Spectral Density Functions for days in which the amount of ordnance disposed were the same in total weight (3,809 lbs.). However, the spectral estimates are different. The mean frequency estimate for the 2006 dataset (40 samples in total) is 0.92 Hz, while the mean for the 2007 (40 samples) dataset is 1.18. This difference is much larger than the error of the AR method, and therefore they can be attributed only to differences in the source. The logs from the disposal contractors indicate that though the total weight of the explosives was similar in the two years, the materials have different chemical characteristics (explosivity). In 2006, the total of 3,809 lbs. was composed of 1,800 lbs. HBX and 2,009-lb. grenades, while in 2007, the composition was 450 lbs. HBX, 1350 lbs. composition B and 2,009 lb.-grenades. HBX is the most energetic in this combination, and we believe that the higher frequency estimated for 2007 is due to less HBX. The operations at Hawthorne will be on going, and in the future there are scheduled detonations of HBX only. We will use these HBX only detonations as references for future investigations on the yield/dominant period relationship.

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